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Performance of the Bowen Ratio Systems on a 22° Slope

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ABSTRACT

The Bowen ratio energy balance technique was used to assess the energy fluxes on inclined surfaces during the First ISLSCP Field Experiment (FIFE). Since air flow over sloping surface may differ from that over flat terrain, it is important to examine whether Bowen ratio measurements taken on sloping surfaces are valid. In this study, the suitability of using the Bowen ratio technique on sloping surfaces was tested by examining the assumptions that the technique requires for valid measurements. This was accomplished by studying the variation of Bowen ratio measurements along a selected slope at the FIFE site. In September 1988, four Bowen ratio systems were set up in a line along the 22 degree north-facing slope with northerly air flow (wind went up the slope). In July of 1989, six Bowen ratio systems were similarly installed with southerly air flow (the wind went down slope). Results indicated that, at distances between 10 to 40 meters from the top of the slope, no temperature or vapor pressure gradient parallel to the slope was detected. Uniform Bowen ratio values were obtained on the slope, and thus the sensible or latent heat flux should be similar along the slope. This indicates that the assumptions for valid flux measurements are reasonably met at the slope. The Bowen ratio technique should give the best estimates of the energy fluxes on slopes similar to that in this study.

INTRODUCTION

The Bowen ratio (Bowen, 1926) energy balance technique (BREB) has become one of the most useful micrometeorological methods for determining sensible and latent heat fluxes. The suitability and accuracy of this technique on horizontal surfaces have been reviewed by a number of scientists (Tanner, 1960; Lourence and Pruitt, 1968; Fuchs and Tanner, 1970; Sinclair et al., 1975; Revheim and Jordan, 1976; Kanemasu et al., 1979; Angus and Watts, 1984). Some researchers have indicated that the Bowen ratio technique has a shorter fetch requirement than other microclimatological techniques based on profiles. Compared to the traditional fetch/height ratio of 100/1 required by most other techniques, a ratio of about 20/1 has been found adequate for the Bowen ratio technique (Fritschen et al., 1983; Heilman and Brittin, 1989). With relatively short and uniform canopies and where there are not extreme differences in energy balance between the surface being studied and the surrounding area, the Bowen ratio technique can be used to describe fluxes from relatively small areas (20 m in diameter).

In recent years, there has been an increased demand for energy flux data from inclined surfaces. The Bowen ratio method has been considered one of the better techniques for measuring the fluxes from sloping surface, because slopes usually do not have an extended homogeneous fetch. In the 1984 ASCOT experiment, several Bowen ratio systems were employed on slopes (Whiteman et al., 1989). During the First ISLSCP Field Experiment (FIFE), 27% of the surface flux stations were located on sloping surfaces tilted

more than 8 degrees, and the Bowen ratio technique was used at these sites (Sellers and Hall, 1990). A previous study showed that the temperature and humidity above sloping surfaces were different from those above flat surfaces, even when surface conditions were similar (Nie et al., 1987). Air flow patterns are affected by slopes when winds cross the isohyets of the slope (Britter et al., 1981; Pearse et al., 1981). Therefore, there are concerns regarding the validity of the micrometeorological measurements of surface energy fluxes made on slopes with the Bowen ratio technique. Although the Bowen ratio technique has already been used to assess the energy balance on sloping surfaces, the validity of using this technique on sloping surface has not been tested with rigorous investigations (Fritschen and Simpson, 1989).

One way to examine whether the measurements made by the Bowen ratio technique are representative on slopes is to compare them with measurements of alternative methods. However, there is no standard method for flux measurements on sloping surfaces. Compared to the Bowen ratio technique, other micrometeorological techniques have similar or even more restrictive assumptions; and thus their validity would be just as, or even more, questionable. For example, slopes do not usually have the extended fetch distance required by most techniques such as the eddy correlation technique. A feasible way to explore this problem is to examine if the requirements for valid measurements with the Bowen ratio technique are reasonably met on sloping surfaces.

Previous studies have indicated that net radiation and soil heat fluxes on slopes can

be measured by instruments (radiometers, heat flux plates) installed parallel to the sloping surface, or reasonably estimated by applying a geometrical correction to the measurements made by horizontally installed instruments (Nie and Kanemasu, 1989; Fritschen and Qian, 1990). With regards to the sensible and latent heat fluxes, the following assumptions need to be met for the Bowen ratio technique to yield valid measurements (Tanner, 1960; Angus and Watts, 1984 Heilman et al, 1989):

(1) the ratio of the turbulent transfer coefficients for heat and water vapor are equal;

(2) the two levels at which the temperature and vapor pressure measurements are made must be within the boundary layer of the air flow which has adjusted to that particular surface, and thus the absence of horizontal gradients.

Numerous studies have shown that these are reasonable assumptions on horizontal surfaces, and successful results have been achieved with the Bowen ratio technique (Tanner, 1960; Fritschen, 1965; Lourance and Pruitt, 1968; Ashktorab et al., 1989). We now consider the validity of these assumptions when the horizontal surface changes to a sloping surface with similar surface conditions. For the first assumption, it should make no difference whether it is a horizontal surface or sloping surface. Therefore, assumptions (1) should be valid on slopes if it is valid on flat surface with similar conditions. In order for the second assumption to be valid, however, the boundary layer in which the measurements are to be made must be fully adjusted to the surface condition of the slope. This implies that no gradients exist in the direction parallel to the slope, and fluxes should be similar for locations within the boundary layer adjusted to a homogeneous slope. Conversely, if the boundary

layer has been fully adjusted to the slope, and thus the gradients are only in the direction perpendicular to the slope, the assumptions for valid Bowen ratio measurements are met. The measurements made by the Bowen ratio method should represent the fluxes of the slope. Hence, the absence of parallel gradients and similar values of the fluxes (and thus the values of Bowen ratio) on a slope are evidences for reasonable measurements by the Bowen ratio method. In this study, the temperature and vapor pressure gradients parallel to the slope and the variation of the Bowen ratio values along the slope are examined to test whether the assumptions for valid Bowen ratio measurements are reasonably met on the slope. The parameter β offers a good alternative of the sensible and latent heat fluxes for this purpose, since the net radiation and soil heat flux are believed to be similar along a homogenous slope.

MATERIALS AND METHODS

When the air flow is at right angles to the direction of the slope (for example, a southerly wind on an east or a west facing slope), it is believed that the slope does not interfere with the air flow differently than a flat surface, and the flux measurements made by the Bowen ratio method should be valid. This study only deals with the cases when the wind direction was either up-slope or down-slope. Separate experiments were conducted at a FIFE surface flux site (site 812) for both conditions of up-slope wind and down-slope wind.

Site description

The study was undertaken on the Konza Prairie Research Natural Area (KPRNA) south of Manhattan, Kansas (N 39.6° and W 115.7°). KPRNA is a 3487 hectare tallgrass prairie managed by the Division of Biology, Kansas State University, for natural ecosystem studies. The experiment site was a 22 degree north-facing slope, about 80 m in length and about 200 m wide. It was one of the surface flux stations for the First ISLSCP Field Experiment (FIFE) in 1988 (site 812). Vegetation on the slope was a typical tallgrass prairie type with big bluestem (*Andropogon gerardii Vitman*) and Indian grass (*Sorghastrum nutans (L.) Nash*) being the dominant species. The texture of the soil was clay loam. At the bottom of the slope there were some large trees; and at the top of the slope there was a fireguard, which separated two burning treatments and also served as an access road (refer to Fig. 1). The slope was unburned. The area south of the fireguard at the top of the slope was burned in April 1989, but not burned in 1988. In 1988, the measurements were made late in the season when the grass had senesced while the trees were still green. Differences in Bowen ratio values, temperature and vapor pressure were anticipated between the grass-covered slope and the tree-covered valley (Fig. 1a). A previous study had indicated differences in fluxes between burned and unburned areas (Watts et al., 1987). The measurements for the 1989 study were made in early July when the prairie was at peak greenness. Therefore, large differences were expected between the hilltop (burned) and the unburned slope (Fig. 1b).

Instrumentation

The AZET Bowen ratio systems (Gay and Greenberg, 1987) were used in this study. They are battery-powered portable systems, each consisting of a data acquisition unit (Hewlett Packard, model HP3421A), a microcomputer (Hewlett Packard, model HP-71b) as the control unit, and an instrument package which included two ceramic wick psychrometers and a position exchange mast. A psychrometer was built with two small, nickel-iron (NiFe) resistance thermometer devices (RTD) which measured dry-bulb and wet-bulb temperatures. The two psychrometers were installed on the exchange mast 0.9 meters apart to measure the temperatures at two heights. The position of the psychrometers were mechanically exchanged every 7.5 minutes to avoid sensor bias. Each year prior to the field experiment, the resistance thermometers were calibrated in a water bath against a quartz thermometer over a temperature range of 0-50 °C. The difference in temperature readings between any RTD and the standard was less than 0.1 °C. Therefore, difference in temperatures between any two RTDs was less than 0.2 °C. This could cause a difference up to 0.3 mb for vapor pressures at temperature of 35 °C. It needs to be pointed out that each temperature reading represents an average of two RTDs, and thus four RTDs were involved in the difference between two systems reported in this study. The differences due to sensor should normally be smaller than 0.2 °C for temperatures and less than 0.3 mb for vapor pressures. However, under extreme circumstances, it could still be up to 0.2°C and 0.3 mb. These sensor differences will affect measurements of the absolute temperature and vapor pressure, but not the Bowen ratio, because the inter-exchange of sensors cancels

systematic errors.

Experimental layout

The experiment for up-slope wind condition was conducted from 18 September to 25 September, 1988, and the one for down-slope wind condition was undertaken from 4 July to 16 July, 1989.

From 17 to 25 September, 1988 (days of year 88261-88269), four systems were installed on the slope 20 meters apart (Fig. 1a). The first system S1 was on the top edge of the slope, and the fourth system S4 was about 60 meters from the top and about 20 meters from the trees. This arrangement was used to test the Bowen ratio technique when the wind was up-slope (northern air flow). The height of the vegetation was about 0.65 m, and the lower psychrometers were 0.9 m above the ground.

As illustrated in Fig. 1b, six Bowen ratio systems were set up in a line down the slope during the 1989 study. The first system (S1) was located south of the fireguard. With a southerly wind, the measurements from S1 represent the properties of the burned area. The second system (S2) was on the top edge of the slope. Distance between S1 and S2 was 12 meters. The third to the sixth systems (S3-S6) were setup down the slope at equal distances (as indicated by d in Fig. 1a). From 4 July to 8 July of 1989 (day of year 89185-89189) the distance d was 10 meters; thus S3 was 10 meters from the top edge of the slope where S2

was located, and S6 was 40 meters from S2. During the period of 9 July to 12 July, 1989 (day of year 89190-89193), S3-S6 were moved closer, so that distance d was 7 meters. The lower psychrometers were about 0.3 meter above the canopy, and the height of the grass was 0.55 meter on day 89185.

In addition to the psychrometers, radiometers and anemometers were also set up to monitor the net radiation, wind speed and wind direction. These measurements were used for data selection, so that data from clear days with the correct wind direction could be selected for the analysis.

Data collection and processing

The following terms which are illustrated in Fig. 2 will be used in the text. The vertical gradients (T_g for temperature and V_g for vapor pressure) are the differences in measurements between two heights of the same system divided by the distance between the upper and the lower psychrometers, δZ (0.9m), which are used to calculate the Bowen ratio β of that system. Strictly, the perpendicular distance δH, rather than the vertical distance δZ, should be used in calculating β. However, this parameter is canceled out in the Bowen ratio calculation.(see equation for β_i in Fig. 2). Air temperature and vapor pressure of a system are measurements of the top level of the system (about 1.2 meters above canopy). The parallel difference of a parameter (ΔT, Δe, or $\Delta \beta$) refers to the difference in measurements of the parameter between systems on different parts of the slope.

Data were collected and processed for 15 minute intervals. Psychrometers exchanged position every 7.5 minutes. After the exchange, the system rested 2.5 minutes for the sensors to equilibrate with the new environment, and then measurements were taken for 5 minutes with 4 readings per minute from each sensor. Two such 7.5-minute periods were combined to make a measuring cycle (15 minutes); thus the instruments completed a measuring cycle with two exchanges before returning to the starting position. For each system, temperature, vapor pressure, and their vertical gradients were computed for each cycle. The Bowen ratio (β) was calculated as follow:

$$\beta = \gamma\ T_g / V_g \qquad (1)$$

where

T_g is the temperature gradient (°C m^{-1});

V_g is the vapor pressure gradient (mb m^{-1});

γ is psychrometric constant (mb °C^{-1}), defined as

$$\gamma = C_p\, P / L\, \epsilon$$

where

C_p is specific heat of air (J kg^{-1} °C^{-1});

L is latent heat of vaporization (J kg^{-1});

ϵ is the ratio of molecular weights of water and air; and

P is the atmospheric pressure (mb).

RESULTS AND DISCUSSION

The days that were chosen in the analysis, information about the experimental layout, wind, soil moisture, and sky conditions were listed in Table 1. Air temperatures, vapor pressures, and Bowen ratios of all the systems are illustrated in Fig. 3 to Fig. 6 to examine their spatial variation along the slope throughout the day. The parallel differences in air temperature (ΔT) and vapor pressure (Δe) between two systems were used in the analysis to examine whether there were differences in air temperature and vapor pressure between two systems in different parts of the slope. The means of the differences and their standard errors are shown in Table 2 and 3. Separate analysis was done for daytime (positive radiation) and nighttime (negative radiation). From this information it can be determined whether the parallel gradients of temperature or vapor pressure exist, since the gradient is proportional to the difference. The variation of Bowen ratio over the slope was also examined, and results were given in Table 4. A t-test was conducted on the differences in Bowen ratio to see if the mean of $\Delta\beta$ was zero. Due to the uncertainty of nighttime Bowen ratio, only daytime data were included in analysis of β. Since the data were sequential and the error of one observation might be correlated with the error of the next observation, in which case the t-test would be invalid, we computed the auto-correlation coefficients, and conducted the Durbin-Watson (DW) statistics test (Durbin and Watson, 1951) for each case to examine the auto-correlation. The auto-correlation was not significant in most cases, so we consider the results of the t-test valid.

Day 88266 was a sunny day with a moderate northerly wind. Being late in the growing season, grasses were in the senescent stage, and the Bowen ratio was high (around 1.5). However, the trees were still green; consequently, lower Bowen ratio and higher latent heat fluxes were anticipated for the valley bottom. Unfortunately, we were unable to make measurements over the trees. From Fig. 3a and 3b, it can be seen that temperatures and vapor pressures were similar for the systems on the slope (S2, S3 and S4). The differences in air temperature between two adjacent systems averaged less than 0.15 °C (Table2), and the differences in vapor pressures had means of less than 0.13 mb (Table 3) for S2, S3 and S4 both during the day and at night. These differences were within the sensor uncertainty and was not significant in the t-test. Therefore, no parallel gradients were detected at a distance of 20-60 meters from the top edge of the slope when the wind blew up-slope.

Comparing the Bowen ratios (β), S2, S3 and S4 gave the same diurnal variations, and the values at any given time were similar. The difference in β averaged -0.116 and -0.085 between S2 and S3 and between S3 and S4, respectively (Table 4). These means of differences were not statistically different from zero.

However, the system (S1) at the top edge of the slope gave significantly lower values of air temperature and vapor pressure, and higher Bowen ratio from those measured on the slope. Compared to the adjacent system (S2), the average difference was 0.496 °C for temperature and 0.359 mb for vapor pressure. The Bowen ratio was about twice as high as on the slope (Fig. 3c). The difference in β averaged 1.521 (Table 3). These results were

a little surprising, and the reason for the unexpected difference is not clear.

In 1989 the Bowen ratio technique was examined on the same slope when the wind was from south (down-slope air flow). Measurements were made in July when the prairie had its maximum green leaf area, and the Bowen ratio was relatively low. The burned area had lower soil moisture and indicated greater water stress than the unburned area. System S1 was in the burned area, and the measurements showed much higher Bowen ratio compared to the unburned slope. The system on the slope edge (S2), while physically located in the unburned area, sensed the air from the burned area and the fireguard. From Fig. 4, 5, and 6 it can be seen that system S2 gave the highest values of β.

Day 89187 (5 July, 1989) was a clear day with a southerly air flow of about 2-3 meter per second for most of the time as measured with an anemometer at the top of the hill. The systems in the burned area (S1) and on the slope edge (S2) measured similar air temperature and vapor pressure (at a height of 1.2 meters above the canopy, Fig. 4a and 4b). The average differences between S1 and S2 were about the same as the instrumental uncertainty. The systems on the slope (S3-S6) showed that the slope was more humid and hotter during the day and cooler at night, compared to the ridge top. Compared to the values obtained from system S2 at the top of the hill, the average air temperature on the slope (S3) was 1.17 °C higher during the day, but 0.726 °C lower at night. The vapor pressure was higher on the slope for both positive radiation period and negative radiation period, with average difference of 1.03 mb and 0.357 mb, respectively. The measurements

also indicated that the properties of air at 10 meters from the slope edge were similar to those at 40 m down slope (Fig. 4). During the daytime, the average difference in temperature or vapor pressure between any two adjacent systems on the slope (from S3 to S6) was less than 0.2 °C, which was of the same magnitude of instrumental difference (Table 2). The difference obtained at night was similar to that during the day. Difference in vapor pressure among the four systems on the slope were less than 0.14 mb. Therefore, no parallel gradients were observed on the slope.

The Bowen ratios on the slope (S3-S6) on 5 July, 1989 (Fig. 4c) were about 0.4-0.5 for most of the day. The values of β at the burned area was about 0.7-1.0 for most of the day. S2 gave the highest Bowen ratio, because there was practically no vegetation on the fireguard due to vehicle traffic. Table 4 shows that the four systems on the slope gave uniform β values with difference between any two systems ranging from -0.038 to 0.044 (about 10%). Although two of the mean differences were statistically different from zero at the 5% level, these differences can still be attributed to sensor uncertainty. A previous study of instrumental comparison showed more than 10% difference in β with identical instruments installed side by side on a flat surface; and this difference tended to be larger (as a percentage) when β was small (Nie et al., 1991). System S6, however, did show a consistently higher β than S3 to S5 (Fig. 4c). In general, β measured by the systems on the slope agreed with one another.

The systems on the slope were moved closer together (the distance d was reduced to

7 m), and measurements were made starting at 10 AM on 9 July, 1989 (day 89191). Data of 9-10 July (89191-89192) are used in the analysis. The weather conditions for these two days were similar to day 187 except for the wind speed which was twice as great (5-6 m s^{-1}).

For measurements made on day 89191, it is shown in Fig. 5 that temperature was about 3-4 °C higher on the slope than at the top of the slope at midday but slightly lower at night, and vapor pressure was about 2 mb higher on the slope than e at the top of the slope. The two systems on the hilltop (S1 and S2) gave similar measurements of T and e. The average difference for air temperature was 0.103 °C during the positive radiation period and 0.009 °C during the negative radiation period. For vapor pressure, the difference averaged 0.202 mb during the day and 0.036 at night. The three systems down the slope (S4-S6) showed similar values of T and e (Fig. 5). The average temperature differences were 0.219 °C (S4-S5) and 0.241 °C (S5-S6) during the day and less than 0.17 °C at night (Table 2). The average vapor pressure differences were 0.203 mb (S4-S5) and -0.030 mb (S5-S6) in the day and smaller than 0.14 mb at night (Table 3). Measurements from S3 (7 meters from the top edge) did not agree with that of the other systems on the slope (S4-S6). The average temperature difference between S3 and S4 was -0.504 for daytime and 0.247 for nighttime (Table 2), and the average vapor pressure differences between the two systems were -0.519 mb and -0.038 mb for day and night, respectively (Table 3). These differences are highly significant, except the vapor pressure difference at night. This suggests the drier and cooler air on the hill top still has some influence on the area at 7 meters from the top when wind speed was about 7 m s^{-1}.

Data obtained on day 89192 are in good agreement with that of day 89191. The daytime differences between the two systems on the hill top (S1 and S2) averaged -0.154 for air temperature and 0.021 mb for vapor pressure, and the nighttime differences are negligible. The three systems down on the slope (S4, S5 and S6) gave essentially the same values, with temperature difference of less than 0.2°C for both day and night, and vapor pressure difference less than 0.2 mb. Large differences were detected between the top edge of the slope (S2) and 7 meters away down to the slope (S3). The average temperature change of -1.329 °C for daytime and 0.553 °C for nighttime, and the average vapor pressure increase were 1.126 mb for daytime and 0.458 mb for nighttime. The differences between S3 and S4 were also significant during the day, with an average of -0.439 °C for temperature and -0.431 for vapor pressure. The nighttime differences were of the same magnitude of instrumental uncertainty.

Fig. 5c and 6c showed that systems S1 and S2 measured high Bowen ratios; the values were greater than 1.0 during most of the day (there were some missing data from system S1 in the afternoon of day 89192). The four systems on the slope (S3, S4, S5 and S6) had similar Bowen ratios with β values being 0.4-0.6 most of the time. The average differences between two adjacent systems were 0.010 (S5-S6), -0.067 (S4-S5), 0.153 (S3-S4) on day 89191, and 0.005 (S5-S6), -0.038 (S4-S5), and 0.103 (S3-S4) for day 89192 (Table 3). The differences of S4-S5 and S5-S6 were not statistically significant. It is noticed that system S3 had β values similar to the other systems on the slope (S4-S6) in the morning, but slightly higher β values in late afternoon. The average differences between S3 and S4 were 0.153

on day 89191 and 0.103 on day 89192, both significant.

SUMMARY AND CONCLUSIONS

Several Bowen ratio systems were set up in a line down a north-facing slope, on which the surface properties were anticipated to be clearly different from that of the horizontal surface in the upwind direction. Air temperatures and vapor pressures measured at different distances from the hilltop were compared; differences of temperature and vapor pressure were inspected along the slope; and the variation of Bowen ratio values were examined. Results showed that no parallel temperature and vapor pressure gradients were detected at a height of 1.2 meter above the canopy, and Bowen ratios were very similar along a distance of 10 to 40 meters from the slope top. These results indicated that the requirements for the Bowen ratio technique are reasonably met on the slope. Considering the difficulties with other methods on slope, the Bowen ratio energy balance technique should give the most reasonable estimates of the fluxes on sloping surface.

This is only a preliminary study of a complicated problem. It indicated that the Bowen ratio technique would give reasonable estimates of sensible and latent heat fluxes on a selected slope within a certain distance of a selected slope. Results may vary with topography, vegetation, wind speed, etc. However, it is encouraging that no parallel gradient was detected, and the uniform β value (therefore the flux value) was obtained on a slope.

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Table 1. Instrument set-up and weather conditions for days selected

Day of year	Number of systems	Distance (d)	Wind direction	Sky condition	Soil moisture content (g/g)
88266	4	20 meters	north	clear	0.245
89187	6	10 meters	south	clear	0.283
89191	6	7 meters	south	clear	not measured
89192	6	7 meters	south	clear	0.225

Table 2. Means and their standard errors for air temperature difference (ΔT, °C) over daytime (positive radiation) and nighttime (negative radiation)

Day of year	Time period	S1-S2	S2-S3	S3-S4	S4-S5	S5-S6
		Difference between				
88266	day	-0.623***	0.129	-0.128		
		±0.098	±0.084	±0.071		
	night	0.197***	-0.087	0.020		
		±0.028	±0.076	±0.031		
89187	day	0.037	-1.172***	0.038	0.039	0.195*
		±0.041	±0.134	±0.025	±0.027	0.069
	night	-0.002	0.726***	0.041	0.058	0.244**
		±0.028	±0.118	±0.039	±0.031	±0.063
89191	day	-0.103 ***	-1.909***	-0.504***	0.219	0.241*
		±0.010	±0.184	±0.175	±0.162	±0.103
	night	0.009	0.638***	0.247***	0.169	0.083
		±0.006	±0.047	±0.033	±0.131	±0.051
89192	day	-0.154*	-1.329***	-0.439**	0.189	0.192*
		±0.061	±0.206	±0.168	±0.109	±0.067
	night	0.006	0.553***	0.013	0.106	0.047
		±0.007	±0.083	±0.012	±0.083	±0.041

*, **, ***: significant at 5%, 1%, 0.1% level, respectively

Table 3. Means and their standard errors for vapor pressure difference (Δe, mb) over daytime (positive radiation) and nighttime (negative radiation)

Day of year	Time period	S1-S2	S2-S3	S3-S4	S4-S5	S5-S6
		------------ Difference between ------------				
88266	day	-0.546***	0.124	0.090		
		±0.015	±0.079	±0.086		
	night	-0.291***	0.031	-0.012		
		±0.069	±0.019	±0.013		
89187	day	-0.257***	-1.025	-0.131	0.093	-0.128*
		±0.032	±0.245	±0.071	±0.052	±0.039
	night	-0.148*	-0.357***	-0.040*	0.019	0.018
		±0.052	±0.106	±0.015	±0.021	±0.024
89191	day	0.232 ***	-1.629***	-0.519***	0.203***	-0.030
		±0.006	±0.073	±0.063	±0.031	±0.042
	night	0.036***	-0.390***	-0.038	0.017	0.131
		±0.003	±0.031	±0.028	±0.009	±0.072
89192	day	0.021***	-1.126***	-0.431***	0.192	-0.125
		±0.005	±0.067	±0.032	±0.098	±0.069
	night	0.034***	-0.458***	-0.210**	0.204	-0.139
		±0.005	±0.069	±0.057	±0.124	±0.076

*, **, ***: Significant at 5%, 1%, 0.1% level, respectively.

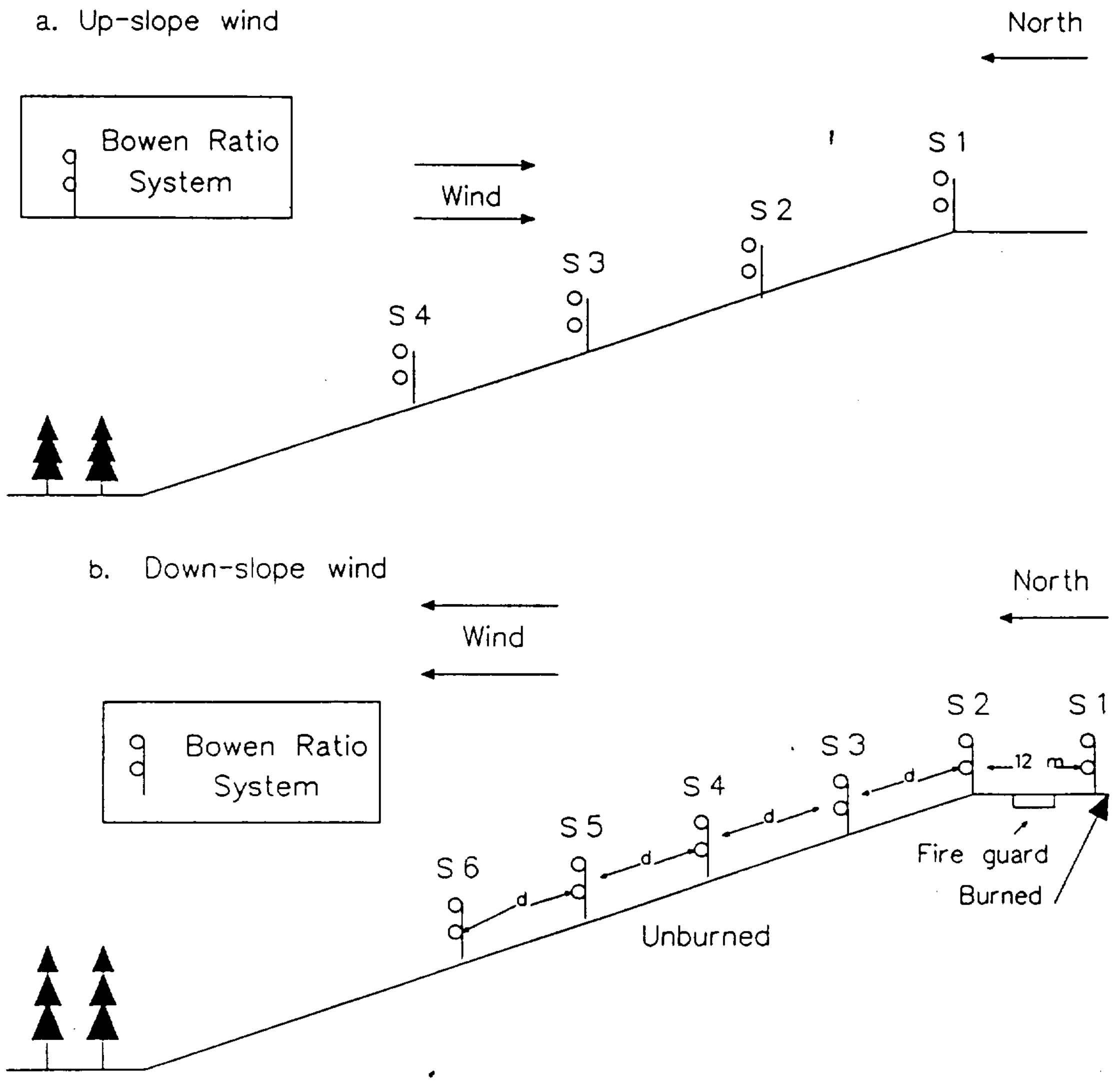
Table 4. Means and thier standard errors for Bowen ratio difference ($\Delta\beta$) over daytime (positive radiaiton)

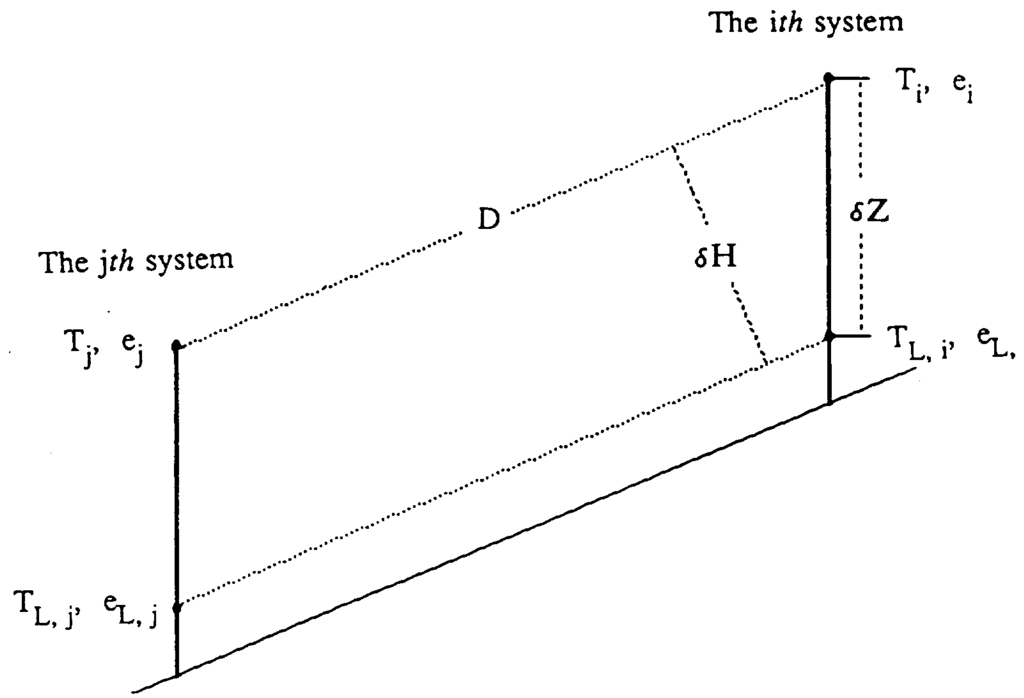
Day of year	Difference between S1-S2	S2-S3	S3-S4	S4-S5	S5-S6
88266	1.521*** ±0.210	-0.116 ±0.078	-0.085 ±0.057		
89187	-0.620*** ±0.052	0.854*** ±0.059	0.044* ±0.015	-0.042 ±0.029	-0.038* ±0.012
89191	0.098* ±0.034	0.856*** ±0.052	0.153* ±0.051	-0.067 ±0.035	0.010 ±0.016
89192	0.187*** ±0.038	1.384*** ±0.250	0.103 *** ±0.019	0.038 ±0.024	0.005 ±0.004

*, **, ***: Significant at 5%, 1%, 0.1% level, respectively

List of Figures

Fig. 6. Comparison of air temperature (a), vapor pressure (b), and Bowen ratio (c) down a north-facing slope with down-slope (southerly wind) on 10 July, 1989. Starting at the top of the slope is sensor system S1 and S2, and system S6 is on the slope 28 meters from the top.


a. Up-slope wind
North
Bowen Ratio System
Wind
S 1
S 2
S 3
S 4
b. Down-slope wind
North
Wind
Bowen Ratio System
S 2
S 1
S 3
12 m
S 4
d
S 5
S 6
Fire guard
Burned
Unburned



For a given system (example: the *ith* system)

$$T_g = \frac{T_i - T_{L,i}}{\delta Z}$$

$$V_g = \frac{e_i - e_{L,i}}{\delta Z}$$

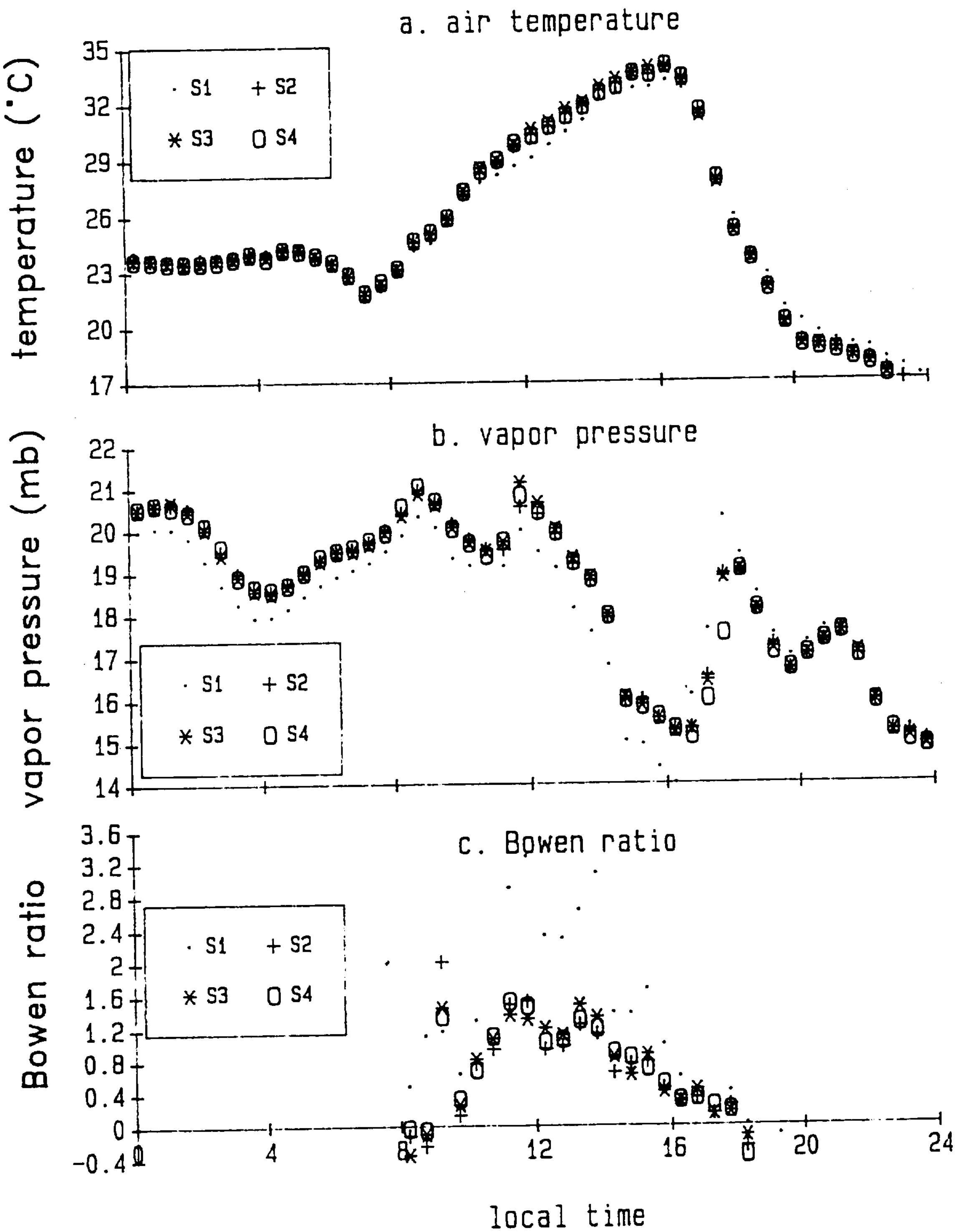
$$\beta_i = \gamma \frac{T_g}{V_g}$$

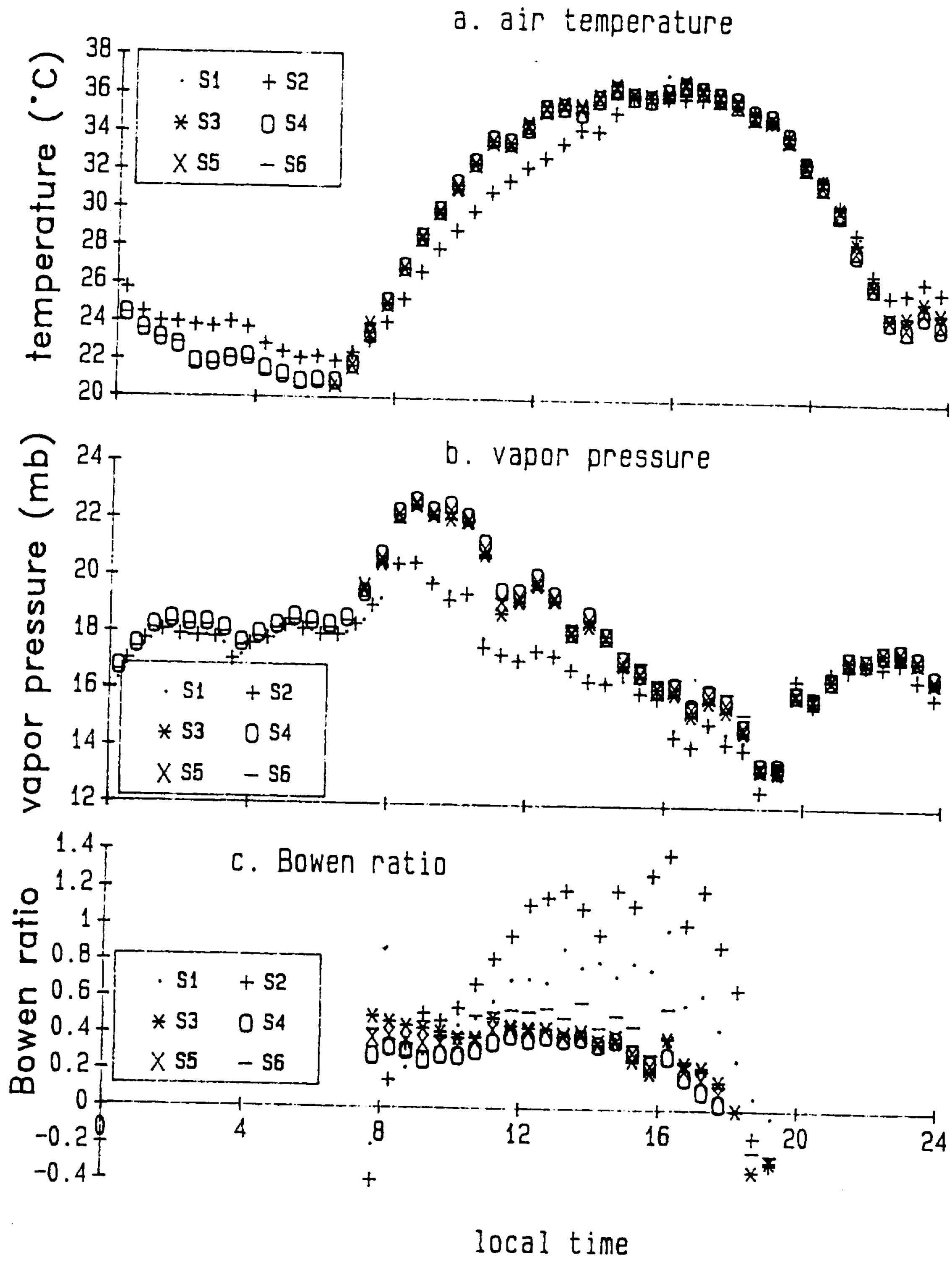
For parallel difference between two systems: (example: the *ith* and the *jth*)

$$\Delta T = T_i - T_j$$

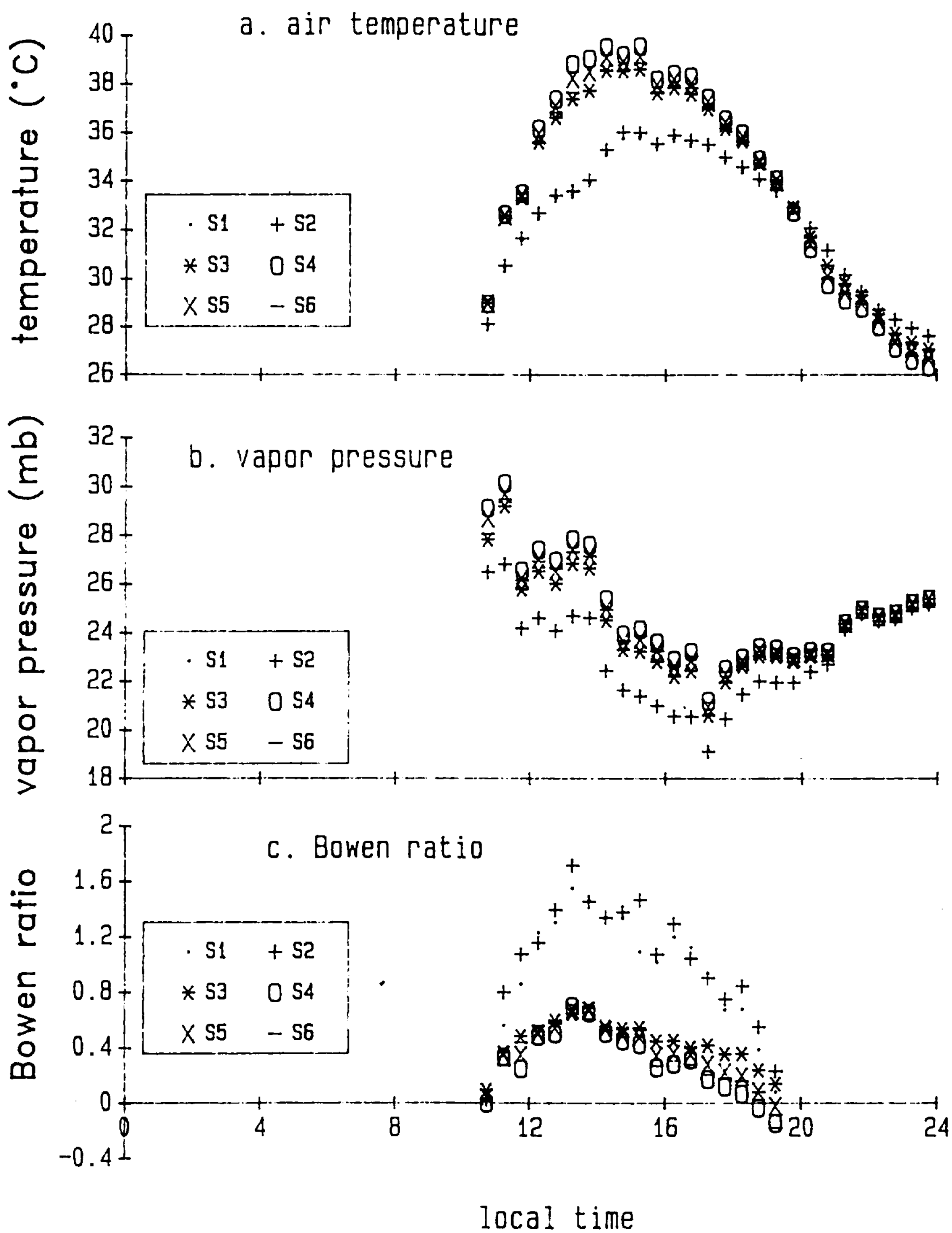
$$\Delta e = e_i - e_j$$

$$\Delta\beta = \beta_i - \beta_j$$

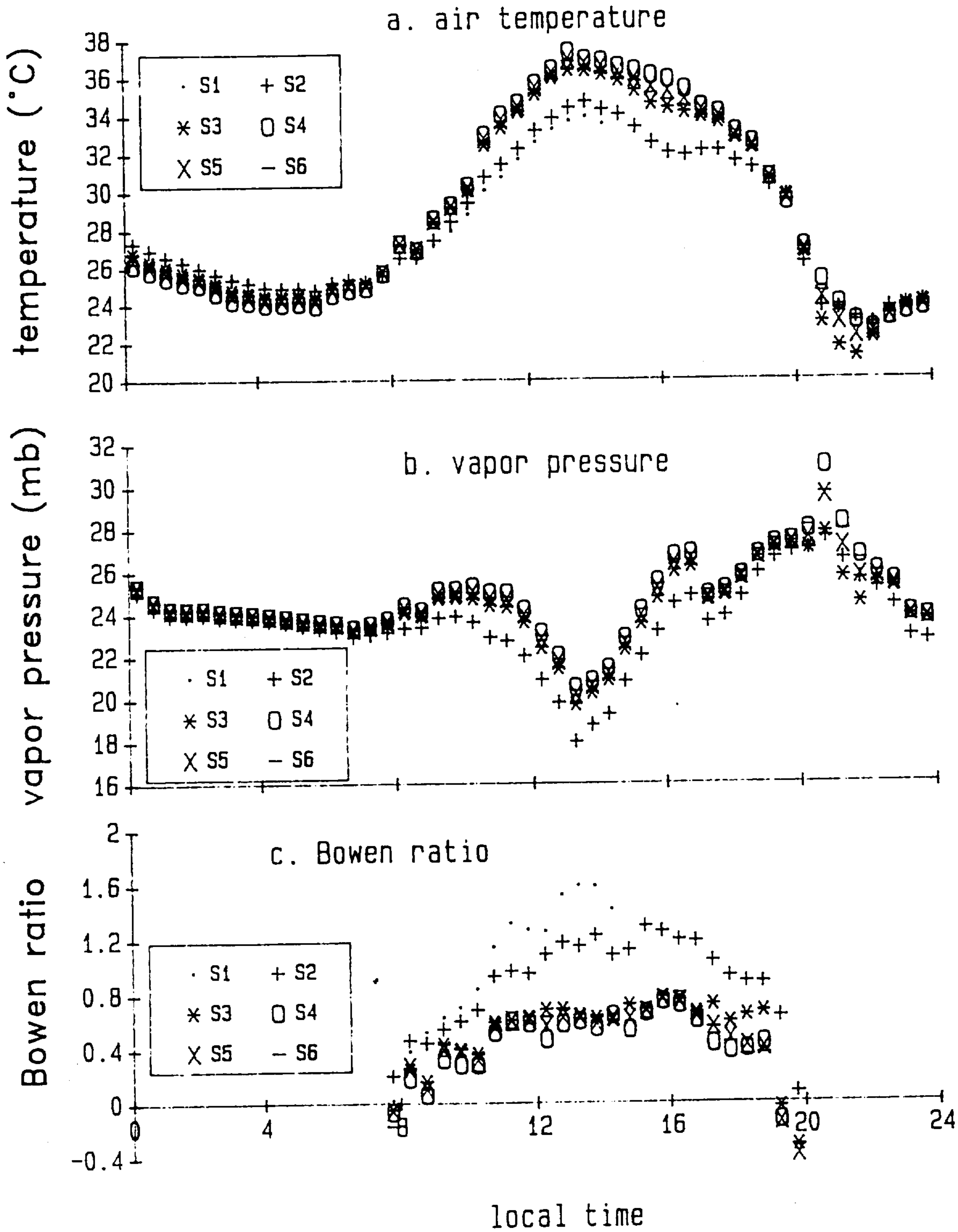

a. air temperature
temperature (°C)
35
32
29
26
23
20
17
· S1
+ S2
* S3
O S4
b. vapor pressure
vapor pressure (mb)
22
21
20
19
18
17
16
15
14
c. Bowen ratio
Bowen ratio
3.6
3.2
2.8
2.4
2
1.6
1.2
0.8
0.4
0
-0.4
0
4
8
12
16
20
24
local time



a. air temperature
temperature (°C)
38
36
34
32
30
28
26
24
22
20
· S1
+ S2
* S3
O S4
X S5
– S6
b. vapor pressure
vapor pressure (mb)
24
22
20
18
16
14
12
· S1
+ S2
* S3
O S4
X S5
– S6
c. Bowen ratio
Bowen ratio
1.4
1.2
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
· S1
+ S2
* S3
O S4
X S5
– S6
0
4
8
12
16
20
24
local time



a. air temperature
temperature (°C)
40
38
36
34
32
30
28
26
· S1
+ S2
* S3
O S4
X S5
– S6
b. vapor pressure
vapor pressure (mb)
32
30
28
26
24
22
20
18
c. Bowen ratio
Bowen ratio
2
1.6
1.2
0.8
0.4
0
-0.4
0
4
8
12
16
20
24
local time


a. air temperature
temperature (°C)
38
36
34
32
30
28
26
24
22
20
· S1
+ S2
* S3
O S4
X S5
– S6
b. vapor pressure
vapor pressure (mb)
32
30
28
26
24
22
20
18
16
c. Bowen ratio
Bowen ratio
2
1.6
1.2
0.8
0.4
0
-0.4
0
4
8
12
16
20
24
local time